

Considerations for the Next Compton Telescope Mission

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Abstract. A high resolution Compton telescope has been identified by the Gamma Ray Astronomy Program Working Group (GRAPWG) as the highest priority major mission in gamma ray astrophysics following GLAST. This mission should provide 25-100 times improved sensitivity, relative to CGRO and INTEGRAL, for MeV gamma ray lines. It must have good performance for narrow and broad lines and for discrete and diffuse emissions. Several instrumental approaches are being pursued to achieve these goals. We discuss issues relating to this mission including alternative detector concepts, instrumental configurations, and background reduction techniques. We have pursued the development of position-sensitive solid-state detectors (Ge, Si) for a high spectral resolution Compton telescope mission. A $\sim 1 \text{ m}^2$ germanium Compton telescope of position-sensitive germanium detectors was the basis for one of the GRAPWG concepts. Preliminary Monte Carlo estimates for the sensitivities of this instrument are encouraging. However, there are technical challenges of cooling large volumes of Ge and providing the large number of spectroscopy channels. We also show that with only two Compton scatter interactions followed by a third interaction, the incident gamma ray energy and direction cone can be precisely determined in detectors with excellent energy and position resolution. Full energy deposition is not required. We present a promising concept for a high efficiency Compton instrument for which thick silicon strip detectors might be preferred.

INTRODUCTION

From the first balloon-borne gamma ray observations in the 1960s to the *COMPTON* Observatory, instrumental sensitivities have improved by about a factor of 100. The *CGRO* instruments achieve these improved sensitivities through a combination of larger areas and longer observation times. ESA's *INTEGRAL* mission will provide modestly improved sensitivities for narrow gamma ray lines from discrete sources. However, significant improvement in sensitivity is required to achieve the desired advances in gamma ray astrophysics. There is a consensus that a high resolution Compton telescope is the best way to meet the broad scientific objectives. The GRAPWG [1] has endorsed such a mission as the highest priority major mission following *GLAST*.

There is a broad range of scientific objectives for the next mission. These include studies of supernovae, novae, compact galactic objects, diffuse galactic emissions, active galactic nuclei, gamma ray bursts, the cosmic diffuse background, and solar activity. Many of the compelling objectives involve gamma ray lines. A target

Table 1. Lines of Astrophysical Interest	
Science Objective	Isotopes and Lines (MeV)
Understand Type Ia SN explosion mechanism and dynamics	⁵⁶ Ni (0.158, 0.812 , ...) ⁵⁶ Co (0.847 , 1.238 , ...) ⁵⁷ Co (0.122)
Map the Galaxy in nucleosynthetic radioactivity	²⁶ Al (1.809 , 0.511) ⁶⁰ Fe, ⁶⁰ Co (1.173 , 1.332) ⁴⁴ Ti (0.068, 0.078, 1.16)
Map Galactic positron annihilation radiation	e ⁺ -e ⁻ annihilation (0.511 , 3 photon continuum) SN Ia ⁵⁶ Co positrons (0.511) ²⁶ Al and ⁴⁴ Ti positrons (0.511)
Understand the dynamics of Galactic Novae	¹³ N, ^{14,15} O, ¹⁸ F positrons (0.511) ⁷ Be (0.478), ²² Na (1.275 , 0.511)
Cosmic Ray Interactions with the ISM	¹² C (4.4), ¹⁶ O (6.1), ²⁰ Ne(1.634), ²⁴ Mg(1.369 ,2.754), ²⁸ Si(1.779), ⁵⁶ Fe(0.847 , 1.238)
Neutron Star Mass-Radius	p-n (2.223)

sensitivity of $10^{-7} \gamma/\text{cm}^2\text{-s}$ (10^6 s observation) has been established as a goal. This is about two orders of magnitude better than *CGRO* or *INTEGRAL*!

Table 1 lists the lines of astrophysical interest. Note that many are in the ~ 0.5 -2 MeV region (bolded in table), an important consideration in the instrumental design.

INSTRUMENTAL CONSIDERATIONS

A high resolution Compton telescope is the preferred instrument for several reasons. It has a very large field-of-view and associated multiplex advantage. Relative to coded aperture or collimated instruments the efficiency, and hence sensitivity, can improve substantially with instrumental configuration. Note that the efficiency of COMPTEL is typically 1% or less. The sensitivities of coded aperture or collimated instruments scale approximately with the square root of the size, making significant advances prohibitive in terms of instrument size and cost. In Compton telescopes, however, the use of position-sensitive detectors with excellent spectral resolution reduces the error in the width of the Compton scatter angle dramatically, thereby providing direct improvement of about a factor of 10 relative to COMPTEL for a similar size instrument.

Finally, a key to improved sensitivity is rejection of internal background. COMPTEL uses time-of-flight to provide good rejection of instrumental background, but it is still the limiting factor in sensitivity. Time-of-flight is not possible with the higher efficiency designs under development or investigation. However, other techniques, using the electron direction of motion and/or background re-construction of events have potential for even better background rejection. The latter depends critically on the energy and position resolution achieved in the detectors.

Candidate Instruments

Several groups are developing instruments or instrument concepts and these are addressed in more detail in other paper in these proceedings. UCR and MPE are developing the TIGRE [2] and MEGA [3] instruments that utilize arrays of thin, position-sensitive silicon detectors as the Compton scatterer. CsI is used as an absorber (the UCR concept also may employ arrays of Ge or CZT pixel detectors for part of the absorber to improve performance). The key advantages are the ability to track the electron through several layers of Si detector, thereby getting the scattered electron's direction and restricting the direction of the incoming gamma ray to a segment of a cone (background reduction). A second advantage is the improved efficiency achieved with these concepts.

Aprile et al. [4] have developed, LXeGRIT, a liquid xenon time projection chamber, which has been successfully flown on a balloon flight. The advantages are excellent 3-D position resolution, moderate efficiency, and the ability to reconstruct the events to reduce internal background. The latter capability is compromised by the relatively poor energy resolution of liquid xenon, but may be improved in gas detectors. [5]

NRL is pursuing an High Resolution Compton Telescope (HRCT) [6] using germanium strip detectors. This would provide the best energy resolution performance but with rather low efficiency. Germanium also requires cooling to liquid nitrogen temperatures, a significant technical challenge for the large volume detector arrays proposed.

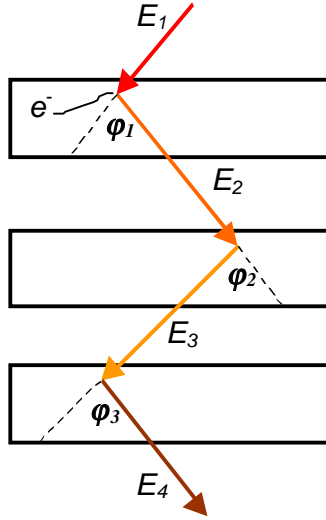
The advantages and disadvantages of the candidate approaches are summarized the Table 2.

TABLE 2. Comparison of Proposed Advanced Compton Telescope Concepts					
	Instrument				
	TIGRE	MEGA	LXeGRIT	HRCT	New Concept
Efficiency	moderate	moderate	moderate	low	high
Energy resolution	Moderate (with Ge or CZT)	poor	poor	excellent	excellent
Position Resolution	good	good	good	good	good
Background rejection	good	good	good	good	excellent
Electron tracking	> 1 MeV	> 1 MeV	> 1 MeV	none	possible
Event reconstruction	no	no	good	excellent	excellent
Line sensitivity	moderate	moderate	moderate	excellent	excellent
Continuum sensitivity	excellent	excellent	excellent	good	excellent

A NEW CONCEPT

Consider a gamma ray, E_1 , incident on a detector or detector array which has good position resolution and good energy resolution. Consider two successive Compton scatter interactions followed by a third interaction as shown in Figure 1, where E_1 , E_2 ,

and E_3 are the incident photon energies for each interaction. The energy losses (to the scattered electrons) are L_1 , L_2 , and L_3 , and the Compton scatter angles are ϕ_1 , ϕ_2 .



$$\cos \phi_1 = 1 - m_e c^2 \left(\frac{1}{E_2} - \frac{1}{E_1} \right) \quad (1)$$

$$\cos \phi_2 = 1 - m_e c^2 \left(\frac{1}{E_3} - \frac{1}{E_2} \right) \quad (2)$$

$$L_1 = E_1 - E_2 \quad (3)$$

$$L_2 = E_2 - E_3 \quad (4)$$

We solve eq. (4) for E_3 and substitute into (2). This yields an equation with E_2 as the only unknown, since ϕ_2 is determined from the locations of the three interactions. Thus the energy E_2 is known, and therefore the incident gamma ray energy, E_1 is also determined from (3), and is given by:

$$E_1 = L_1 + \frac{L_2}{2} + \frac{1}{2} \left[L_2^2 + \frac{4m_e c^2 L_2}{1 - \cos \phi_2} \right]^{\frac{1}{2}} \quad (5)$$

where $m_e c^2$ is the rest mass of the electron. The direction cone of the incoming gamma ray can then be determined from eq (1) just as for a conventional Compton telescope. The uncertainties in E_1 and ϕ_1 can also be determined, and setting $X = 4m_e c^2 / (1 - \cos \phi_2)$, are:

$$dE_1 = \left[dL_1^2 + \left(\frac{1}{2} + \frac{1}{4} [L_2^2 + XL_2]^{\frac{1}{2}} [2L_2 + X] \right) dL_2^2 + \left(\frac{\sin \phi_2}{4} [L_2^2 + XL_2]^{\frac{1}{2}} \left[\frac{XL_2}{(1 - \cos \phi_2)} \right] \right)^2 d\phi_2^2 \right]^{\frac{1}{2}} \quad (6)$$

$$d\phi_1 = \frac{m_e c^2}{\sin \phi_1} \left[\left(\frac{1}{(E_1 - L_1)^2} - \frac{1}{E_1^2} \right) dE_1^2 + \frac{dL_1^2}{(E_1 - L_1)^4} \right]^{\frac{1}{2}} \quad (7)$$

where dL_1 and dL_2 are the errors in the energy loss at the Compton scatter sites and $d\phi_2$ is the error in the scatter angle ϕ_2 . The uncertainty in the width of the scattering angle must also be combined with an uncertainty in the axis of the direction cone. There is also an additional uncertainty in both E_1 and $d\phi_1$ associated with the atomic velocity of the scattered electron [7]. With excellent energy and position resolution in the individual array elements, it will be possible to determine the incoming gamma ray energy and scatter angle to typically a few keV and 1° or less, respectively.

This concept offers several new possibilities. The requirement for only two Compton scatter interactions plus a third interaction means that high-Z materials are not required. Therefore, high resolution detectors (e.g. Ge, Si, CZT, strip or pixel detectors or possibly high purity gas detectors) are good candidates. Si is an attractive choice [8] since Si detectors can be operated at or near room temperature, thereby avoiding the cryogenic requirements of Ge. The performance of an instrument using this approach is very dependent on the energy resolution and position resolution achieved.

One of the major advantages of an instrument using this concept is a very high efficiency. Efficiencies as high as 25-50% in the MeV region are possible. Achieving high efficiencies will require a large fraction of active detector volume relative to passive materials (structure, housings, and electronics). The instrument will inherently have a very large field-of-view. Achieving the desired 10^{-7} $\gamma/\text{cm}^2\text{-s}$ sensitivity will also require good background reduction. This should be achieved through the use of event re-construction for all events, both external and internal. The internal background events, such as radioactive spallation products and neutron capture cascades, should be efficiently rejected because the re-construction of these events do not lead to valid Compton scattering sequences. The efficiency of such background rejection will be very dependent on the energy resolution and position resolution of the detectors [9], again placing very high priority on use of the best position-sensitive detectors available (e.g. Ge or Si strip detectors).

ACKNOWLEDGEMENTS

We acknowledge support from the Office of Naval Research and from NASA under Grant W19390.

REFERENCES

1. Recommended Priorities for NASA's Gamma Ray Astrophysics Program, NP-1999-04-072-GSFC
2. O'Neill, T., et al., these proceedings (2000)
3. Schopper, F., et al., these proceedings (2000)
4. Aprile, E., et al., these proceedings (2000)
5. Aprile, E., et al., SPIE **3446**, 88 (1998)
6. Kroeger, R.A., et al., these proceedings (2000)
7. Kamae, T., et al., Nucl. Instr. Meth. **35** 352 (1988)
8. Momayesi, M., Warburton, W.K., and Kroeger, R.A., SPIE Vol. **3768** 530 (1999)
9. van der Marel, J. and Cederwall, B., preprint submitted to Elsevier(1999)